Theory of Strong Intrinsic Mixing of Magnetic Particle Suspensions in Vortex Magnetic Fields

by **J. E. Martin**

Motivation—Although there are countless methods of fluid mixing, none of these has proven successful on the microscale. Even simple mixing cells have proven unsuccessful because it is difficult to create flow rates large enough to initiate turbulence. We have discovered that strong magnetic mixing occurs when magnetic particle suspensions are subjected to a "vortex" magnetic field - a rotating field in combination with a dc field normal to the rotating field plane, Fig. 1.

Experimental work in our laboratory shows that vortex field mixing has surprising properties. The mixing torque is *independent* of the field frequency and liquid viscosity, and proportional to the field squared. Mixing with a magnetic stir bar is quite different: the torque is proportional to the field frequency and liquid viscosity, and independent of the field strength. Of course, in each case there are stagnation conditions where mixing does not occur, such as an inadequate field, or a field frequency that is too high.

Our challenge is to develop a microscopic model of vortex field mixing that agrees with experimental observations, and predicts the dependence of the torque on particle size. If the torque is independent of the particle size, then a new technology can be scaled to any size.

Accomplishment—From the details of our experimental observations we deduced that the mixing in vortex fields is due to the formation of particle chains that have a precessional motion. These chains are held together by the dipolar interactions between particles. The field creates a torque on a chain because it lags behind the field. A Brownian Dynamics code we developed confirms the existence of these chains.

Our theoretical analysis, summarized in Fig. 2, shows that the orbits of these chains lie on the surface of a cone. The chain cone angle θ is the vortex field angle for short chains, but becomes progressively smaller for longer chains, which lag the field by a greater phase angle ϕ. If chains grow without limit, then eventually the cone angle will vanish, and mixing will not occur.

Whether or not this mixing catastrophe occurs is dependent on the vortex field angle. For vortex field angles greater than 45° chains cannot grow without limit because they become unstable or metastable. These instabilities, shown Fig. 2, are associated with the competition between the dipolar and hydrodynamic torque, as well as the fact that the radial dipolar interaction between enchained particles can become repulsive for large chain phase lags. We have confirmed these instabilities with single-chain simulations. The overall physical picture is one in which volatile chains grow to their stability limit, regardless of field frequency, strength, or liquid viscosity. This theory accounts for all of the experimental observations, and predicts that the mixing torque is independent of the particle size.

Significance—Mixing in a vortex magnetic field is a very simple and powerful method of mixing on the microscale, such as in irregular microfluidic devices. The mixing torque is independent of particle size, and the mixing is uniform throughout even complex volumes. This quantitative theory identifies the factors that optimize torque, and gives quantitative predictions for any given conditions.

Sponsors for various phases of this work include: DOE Office of Basic Energy Sciences

Contact: James E. Martin, Nanomaterials Sciences, Dept. 1112
Phone: (505) 844-9125, Fax: (505) 844-4045, E-mail: jmartin@sandia.gov

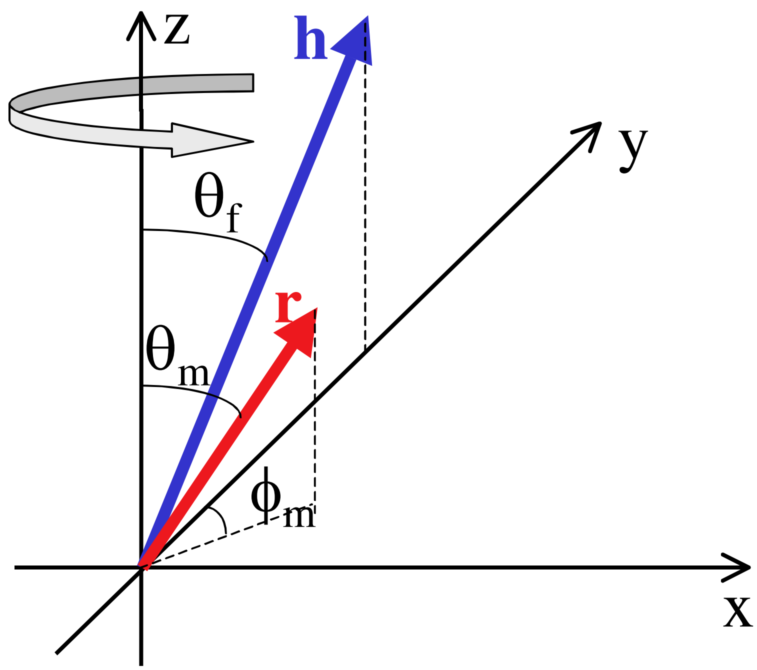

Figure 1. The field **h** rotates around the z axis at a vortex (or cone) angle θ_f. The chain, indicated by the vector **r**, follows the field at some phase lag angle ϕ_m, and at cone angle $\phi_m < \theta_f$.

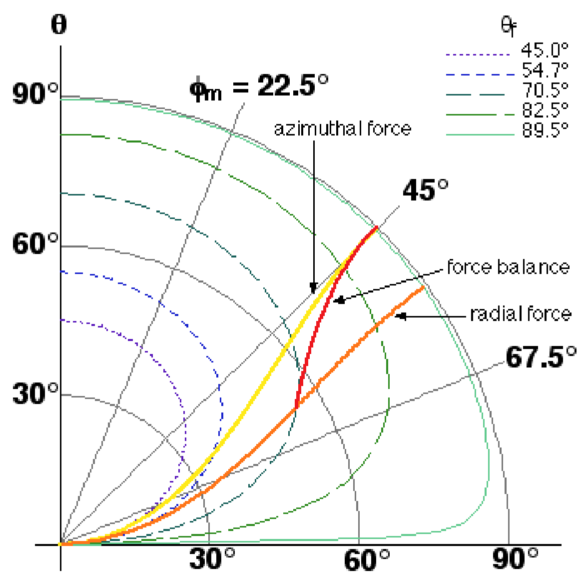

Figure 2. A polar plot of the stationary orbits of chains following a vortex field. (The radial distance is the polar angle θ and the phase lag ϕ_μ is the standard polar azimuthal angle.) This polar plot has a direct physical interpretation: Each point on the locus of stationary orbits can be thought of as the point at which the chain vector intersects an *x*-*y* plane with *z*=1 at the instant at which the applied field is in the *y*-*z* plane. In yellow, orange and red are the various instabilities that can occur.